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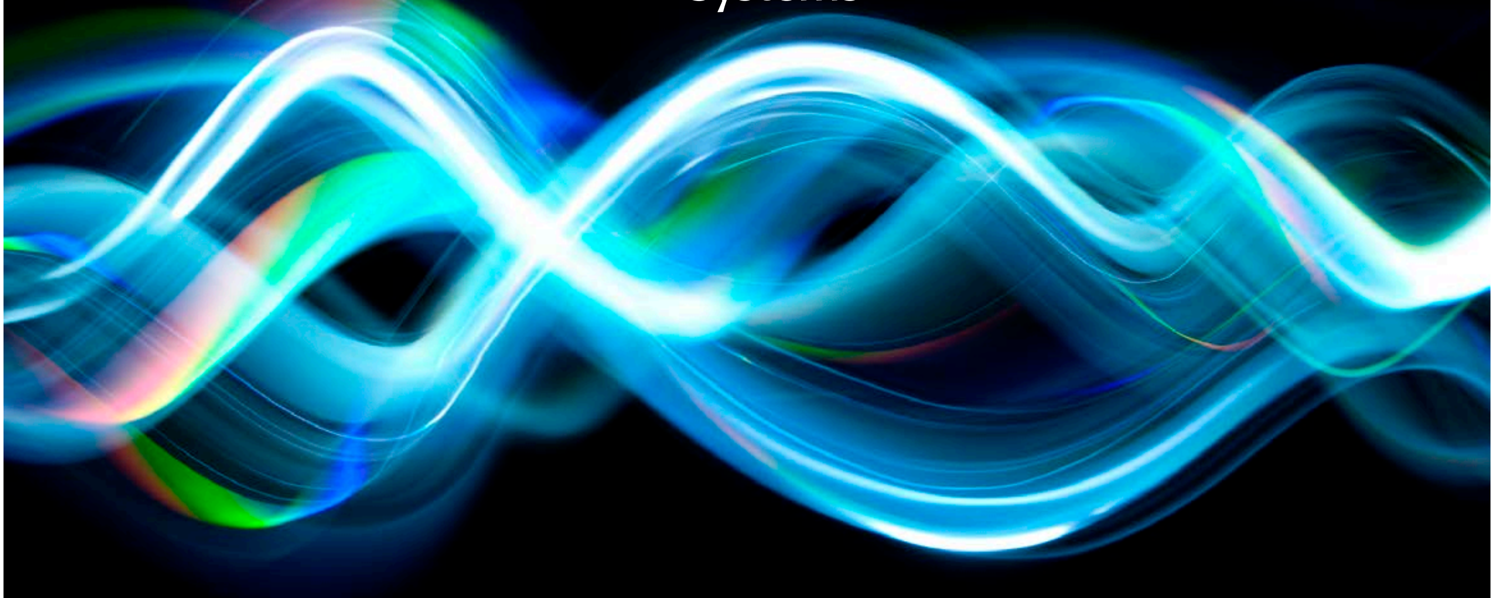
IEEE Std 3003.2™-2014

Recommended Practice for Equipment Grounding and Bonding in Industrial and Commercial Power Systems



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IEEE Recommended Practice for Equipment Grounding and Bonding in Industrial and Commercial Power Systems

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Abstract: The grounding and bonding of equipment in industrial and commercial power systems is covered in this recommended practice. The interconnection and grounding of the non-electrical metallic elements of a system is covered first. This is followed by a discussion of the objectives of equipment grounding and bonding, including minimizing electric shock hazard to personnel, providing adequate current carrying capability for ground faults, and ensuring the timely operation of overcurrent protection.

Keywords: bond, electrode, ground, grounded, grounding, IEEE 3003.2™

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Introduction

This introduction is not part of IEEE Std 3003.2™-2014, IEEE Recommended Practice for Equipment Grounding and Bonding in Industrial and Commercial Power Systems.

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This recommended practice was developed by the Technical Books Coordinating Committee of the Industrial and Commercial Power Systems Department of the Industry Applications Society as part of a project to repackage the popular IEEE Color Books®. The goal of this project is to speed up the revision process, eliminate duplicate material, and facilitate use of modern publishing and distribution technologies.

When this project is completed, the technical material in the thirteen IEEE Color Books will be included in a series of new standards—the most significant of which will be a new standard, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new standard will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional dot standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000™:

— Power Systems Design (3001 series)
— Power Systems Analysis (3002 series)
— Power Systems Grounding and Bonding (3003 series)
— Protection and Coordination (3004 series)
— Emergency, Standby Power, and Energy Management Systems (3005 series)
— Power Systems Reliability (3006 series)
— Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a dot standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

The material in this recommended practice largely comes from Chapter 2 of IEEE Std 142™-2007 (*IEEE Green Book*™).

IEEE Std 3003.2™

This recommended practice provides fundamental concepts and recommended procedures for equipment grounding of power apparatus, wiring systems, interior and exterior substations, and utilization equipment.

Contents

IEEE Recommended Practice for Equipment Grounding and Bonding in Industrial and Commercial Power Systems

1. Overview

1.1 Scope

This recommended practice covers the grounding and bonding of equipment in industrial and commercial power systems. The interconnection and grounding of the non-electrical metallic elements of a system is covered first. This is followed by a discussion of the objectives of equipment grounding, including minimizing electric shock hazard to personnel, providing adequate current carrying capability for ground faults, and ensuring the timely operation of overcurrent protection.

1.2 General

The practices set forth herein are primarily applicable to industrial, institutional, or commercial power systems.

Where distances or power levels may dictate circuitry and equipment similar to a utility, consideration of utility practices is warranted. In addition to the general technical considerations in the practice of grounding as discussed in this recommended practice, as well as pertinent codes or standards imposed by local

regulatory authorities, particular needs of service and the experience and training of the workforce should also be considered.

The National Electrical Code® (NEC), NFPA 70®,[1] sponsored by the National Fire Protection Association, contains recommendations pertaining to system and equipment grounding applicable to industrial, commercial, and special occupancy facilities. The requirements of the NEC address the fundamental principles of safety, as does Section 131 of International Electrotechnical Commission (IEC) Standard 60364-1, Electrical Installations of Buildings. These codes, when adopted by government entities, become mandatory. They are considered minimum requirements for the protection of life and property and should be carefully reviewed during the course of system design. The recommended practices in this document are intended to supplement, and not negate, any of the requirements in the NEC, IEC, or any other location-specific regulatory codes.

The recommended practices in this document are intended to provide explanations of how electrical systems operate. A better understanding of the electrical principles will assist the engineer in implementing the recommendations in a manner that best provides for the needs of a specific design function.

1.3 Covered—equipment grounding and bonding

The terms grounded and bonded are defined in the CEC, IEC, National Electrical Safety Code® (NESC®) (Accredited Standards Committee C2-2012), and NEC. Bonding is the electrical interconnecting of conductive parts designed to achieve a low-impedance conductive path. This definition is self-explanatory and implies that the conductive path should be adequately sized, and connections properly installed, in order to maintain a path with impedance as low as possible. The term bonding obviously is not exclusive to grounded systems. Grounded means connected to, or in contact with, the earth, or connected to some extended conductive body that serves in place of the earth, whether the connection is intentional or accidental. The earth or the other conductive body is known as the ground in North America and areas of the world that use the CEC or NEC, and earth in the areas of the world that use the IEC. When used as a verb, grounding is the act of establishing the aforementioned connection to ground or the conductive body. When used as an adjective, grounding describes the conductor or metal part that is used to make the connection to ground.

There are two different types of permanent grounding relative to electrical work. One type enhances the safety of the electrical system, and the second enhances the safety of the electrical equipment. The first type is system grounding. System grounding is attaching at least one point of the normal current-carrying electrical path-to-ground, either solidly or through an impedance. The system ground affects performance of the electrical system, making it more stable and predictable. From a safety viewpoint, system grounding limits the potential difference between uninsulated objects in an area, helps limit the magnitude of overvoltages due to transients, and provides the reference point for the return of fault currents so that faults can be isolated quickly. System grounding is covered in Chapter 1 of IEEE Std 142™-2007 (*IEEE Green Book*™).

The second type is equipment grounding, which provides significant protection for the electrical equipment and for any people in close proximity to it. Equipment grounding is the act of bonding all non-current-carrying conductive objects together to create a low-impedance conductive path (or body) to the source, which is connected to the system ground. In NEC terminology, these functions are performed by the equipment grounding conductor (EGC), and in IEC terminology by the protective earth (PE) conductor. In this document, the term protective conductor will be used in place of the NEC term or the IEC term in order to stress that these dual functions of grounding and bonding are being done for safety purposes. Grounding and bonding will also be used throughout this document as appropriate.

The purposes for equipment grounding and bonding are:

[1] Information on references can be found in Clause 2.

a) Providing a permanent low-impedance path for fault currents to return to the source when there is a failure and the currents are not flowing on the normal current-carrying path.
b) To minimize the shock hazard during an electrical failure to anyone in contact with the failed equipment.
c) To minimize shock hazards due to lightning strikes and reduce the possibility of fire or explosion.

1.4 Not covered—system grounding

As a component of power distribution systems, system grounding is the intentional connection-to-ground of a phase or neutral conductor for the purpose of:

a) Controlling the voltage with respect to earth, or ground, within predictable limits, and
b) Providing for a flow of current that will allow detection of an unwanted connection between system conductors and ground. Such detection may then initiate operation of automatic devices to remove the source of voltage from these conductors.

System grounding is presently covered in Chapter 1 of IEEE Std 142-2007 (*IEEE Green Book*).

1.5 General

The need for equipment grounding and bonding exists for high-impedance, low-impedance, and effectively grounded systems as well as for ungrounded systems. Examples of components of the equipment grounding and bonding system include metallic raceways, motor frames, equipment enclosures, and protective conductors (wires). Typical regulatory requirements for equipment grounding and bonding are as follows:

a) Conductive materials enclosing electrical conductors or equipment, or forming part of such equipment, should be connected to earth so as to limit the voltage-to-ground on these materials. Where the electrical system is required to be grounded, these materials should be bonded together to form part of the grounding system and should be bonded to the supply system neutral conductor at the source and/or the main service panel.
b) Where the electrical system is not solidly grounded, these materials should be bonded together in a manner that establishes an effective means of limiting the voltage potential between the conductive materials or ground.
c) Electrically conductive materials that are likely to become energized should be bonded to the supply system grounded conductor at the source in a manner that establishes an effective path for fault current.
d) The earth should not be used as the sole protective conductor or fault current path.

1.6 Objectives

The basic objectives of an equipment grounding and bonding system are the following:

a) To reduce electric shock hazard to personnel by preventing dangerous voltages or currents within any conductive materials which may become energized or may carry current during an electrical fault which involves ground.
b) To provide adequate current-carrying capability, both in magnitude and duration, for the overcurrent protection system to operate, without creating a fire or explosive hazard to building or contents, or degrading the conductors by the flow of ground-fault currents in excess of its short time thermal rating.

c) To provide a low-impedance return path for ground-fault current necessary for the timely operation of the overcurrent protection system.

1.7 Electric shock exposure

Electric shock injuries result from contact with metallic components that are energized, whether intentionally or unintentionally. Effective equipment grounding and bonding practices can minimize these personal injuries.

A breakdown of basic insulation can cause accidental contact between an energized electrical conductor and the metal frame that encloses it. Such contact will energize the frame to the voltage level of the conductor. Safety considerations require that the level of the shock-hazard voltage be minimized as much as possible to a less hazardous level. The equipment grounding and bonding system should do this by forming a low-impedance path back to the source and thereby facilitating the operation of the circuit protective device.

The impedance of the protective conductor should be low enough to accept the available line-to-ground-fault current without creating a hazardous voltage drop across the conductor. Therefore, the available ground-fault current of the supply system will have a direct bearing on the protective conductor requirements.

1.8 Thermal capability

The grounding conductor should also function to conduct the available ground-fault current (magnitude and duration) without excessive temperature rise or arcing. The use of a large cross-section grounding conductor is not good enough. All parts of the fault circuit, including the terminations and other parts, should be capable of carrying the fault current without distress. The installation should also provide a lower impedance fault return path than other possible parallel paths that may have inadequate current-carrying capacity.

It is apparent that fires can and do originate in electrical systems. Effective design, installation, and maintenance of equipment grounding systems are a vital element in reducing these fire hazards.

Joints and connectors are critical components of the fault return path. Good workmanship is essential to a safe system and should be demanded. Supervision of installation, inspection, and proper maintenance should assure that the grounding system is not compromised. The use of a supplementary (redundant wire) protective conductor, in addition to metallic conduit, where used, is recommended to assure the continuity of the equipment grounding system. Non-conductive coatings on equipment to be bonded should be removed from threads or other contact surfaces to ensure good electrical continuity. Connections that will be inaccessible, such as those that will be below grade, should be made with compression fittings or exothermic welds.

One critical connection is the locknut connection between metallic raceway or cable and a sheet metal enclosure. Particular assurance that this connection be made and maintained clean and tight is imperative. Non-conductive coatings on equipment to be grounded should be removed from threads or other contact surfaces to ensure good electrical continuity. A grounding bushing with its terminal bonded to an adequate terminal within the enclosure is recommended for all applications.

1.9 Overcurrent protection operation

The equipment grounding and bonding system is an essential part of the overcurrent protection system. The overcurrent protection system requires a low-impedance ground return path in order to operate promptly

and properly. The earth as the ground return path is rarely of low enough impedance and is not intended to be the only return path. The impedance of the protective conductor should be low enough that sufficient ground-fault current will flow to operate the overcurrent protective device and clear the fault rapidly.

In ac applications, the total impedance (R + jX) controls the current division among paralleled paths. Circuit inductance is a function of conductor spacing, so the inductance of low-ampacity circuits is often negligible. This is especially true in low-voltage systems where physical spacing is not required for dielectric strength. But in medium and high-voltage circuits, the spacing that must exist between conductors tends to make inductance far more significant than resistance. Because reactance increases significantly with conductor separation, reactance is the predominant element of impedance for open wire and tray systems for circuits rated above 200 A (see Figure 12). For cable systems or conductors in conduit with close proximity, reactance is a significant component of impedance for circuits rated over 200 A. The reactance of an ac circuit is determined mainly by the spacing between outgoing and return conductors and is only slightly affected by conductor size (see Figure 12). The circuit resistance is directly affected by conductor size. Therefore the ratio of X/R and the relative effect of reactance on circuit impedance increases as the conductor size increases.

NOTE—Increased separation spacing between grounding and phase conductors increases not only the reactance Xg of the grounding conductor but also the zero-sequence reactance X_0 of the circuit.[2]

In 60 Hz ac circuits rated above 40 A, it becomes mandatory that the installed protective conductor be physically placed to present a much lower reactance than other less capable parallel paths. The manner in which this is achieved is treated in Clause 4.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 60364-1, Electrical Installations of Buildings.[3]

IEEE Std 80™, IEEE Guide for Safety in AC Substation Grounding.[4,5]

IEEE Std 142-2007 (*IEEE Green Book*), Recommended Practice for Grounding of Industrial and Commercial Power Systems.

IEEE P3000™/D1, Draft Recommended Practice for the Engineering of Industrial and Commercial Power Systems.[6]

NFPA 70, National Electrical Code® (NEC®).[7]

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[2] Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.
[3] IEC publications are available from the Sales Department of the International Electrotechnical Commission, 3 rue de Varembé, PO Box 131, CH-1211, Geneva 20, Switzerland (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org).
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[7] NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA (http://www.nfpa.org/).

3. Definitions, acronyms, and pictorial guide

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause. [8]

3.1 Grounding and bonding terminology

Figure 1 illustrates defined elements in a typical equipment grounding application.

basic insulation: The insulation applied to live parts necessary to provide the first line of protection against electric shock.

bond (bonding): The electrical interconnecting of conductive parts, designed to achieve a low-impedance conductive path.

bonding jumper: A reliable conductor to ensure electrical conductivity between metal parts. Equivalent to IEC term protective bonding conductor (PBC).

direct contact: Contact with parts of the installation normally live.

equipment bonding jumper: The connection between two or more portions of the equipment grounding conductor.

equipment grounding: *See*: **equipment grounding and bonding**.

equipment grounding and bonding: (A) For grounded systems: The act of bonding all non-current-carrying conductive objects together to create a low-impedance conductive path (or body) to the source, which is connected to the system ground. **(B)** For ungrounded systems: The act of bonding all non-current-carrying conductive objects to ground (earth). For ungrounded system (primary) supplying a grounded system (secondary), the bonding would include connection to the grounding system for the secondary side.

equipment grounding conductor (EGC): *See*: **protective conductor**.

exposed-conductive-part (ECP): A conductive part, forming part of electrical equipment, which can be touched which is not live, but which may become live when basic insulation fails. A conductive part, which can be energized just because it is in touch with an ECP, should not be considered an ECP. ECPs may be referred to as non-current-carrying metal parts.

extraneous-conductive-part (EXCP): EXCP is a conductive part, which can be touched, not forming part of the electrical system, and liable to introduce a zero potential or an arbitrary potential. Both potentials are dangerous. Examples of extraneous-conductive-parts are the metalwork for gas, water, and heating systems; the metallic frame of a building; conductive floors and walls; etc.

ground: A conducting connection, whether intentional or accidental, between an electrical circuit or equipment and the earth, or to some other body that serves in place of the earth. This term is considered equivalent to the term earth as used in common terminology outside North America.

grounded: Connected to earth or to an extended conducting body that serves instead of the earth, whether the connection is intentional or accidental.

[8] *IEEE Standards Dictionary Online* subscription is available at:
http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

grounding electrode: A conductor or group of conductors in intimate contact with the earth for the purpose of providing a connection with the ground.

grounding electrode conductor (GEC): A conductor used to connect the system grounded conductor or the equipment to a grounding electrode or to a point on the grounding electrode system.

grounded system: A system in which at least one conductor or point (usually the middle wire or neutral point of transformer or generator windings) is intentionally grounded, either solidly or through an impedance.

grounding system: A system that consists of all interconnected grounding connections in a specific power system and is defined by its isolation from adjacent grounding systems. The isolation is provided by transformer primary and secondary windings that are coupled only by magnetic means.

indirect contact: Contact with metal parts not normally live, but energized under fault conditions. (The basic difference between the direct and indirect contact is the presence, between the live part and the person, of a metal enclosure).

local ground: Part of the earth in electric contact with a grounding electrode that may have an electric potential of other than zero.

main bonding jumper: The connection between the grounded circuit conductor and the equipment grounding conductor at the service.

protective conductor: The conductor provided for protective functions, such as providing a path for fault current to flow back to the source, for connecting non-current-carrying metal parts of equipment, raceways, and other enclosures to earth, etc. There are often specific names for this conductor, such as equipment grounding conductor (EGC) in the NEC, protective earth conductor (PE) in the IEC, and bonding conductor (BC) in the CEC.

protective earth conductor (PE): *See*: **protective conductor**.

protective earth neutral (PEN): A conductor that combines the functions of the protective conductor and the neutral conductor, used in some IEC grounding systems.

neutral conductor: The conductor connected to the neutral point of a system that is intended to carry current under normal conditions.

remote ground: Part of the earth outside the influence of a grounding electrode with a potential commonly taken as zero.

3.2 Acronyms not defined in definitions section

AWG	American wire gauge (standard wire sizes used in the U.S.)
BX	Older version of armored cable, replaced by type AC (armored cable)
CEC	Canadian Electric Code
NEC	National Electrical Code (NFPA 70, U.S.)
NESC	National Electrical Safety Code
SCR	silicon controlled rectifier
VCI	varnished cambric insulation

3.3 Terminology pictorial guide

Figure 1 provides a pictorial guide to grounding and bonding elements as used within this recommended practice. In Table 1, equivalent IEC terms are provided for Figure 1 tags as an alternative to inclusion of dual terminology such as ground (earth) throughout the document.

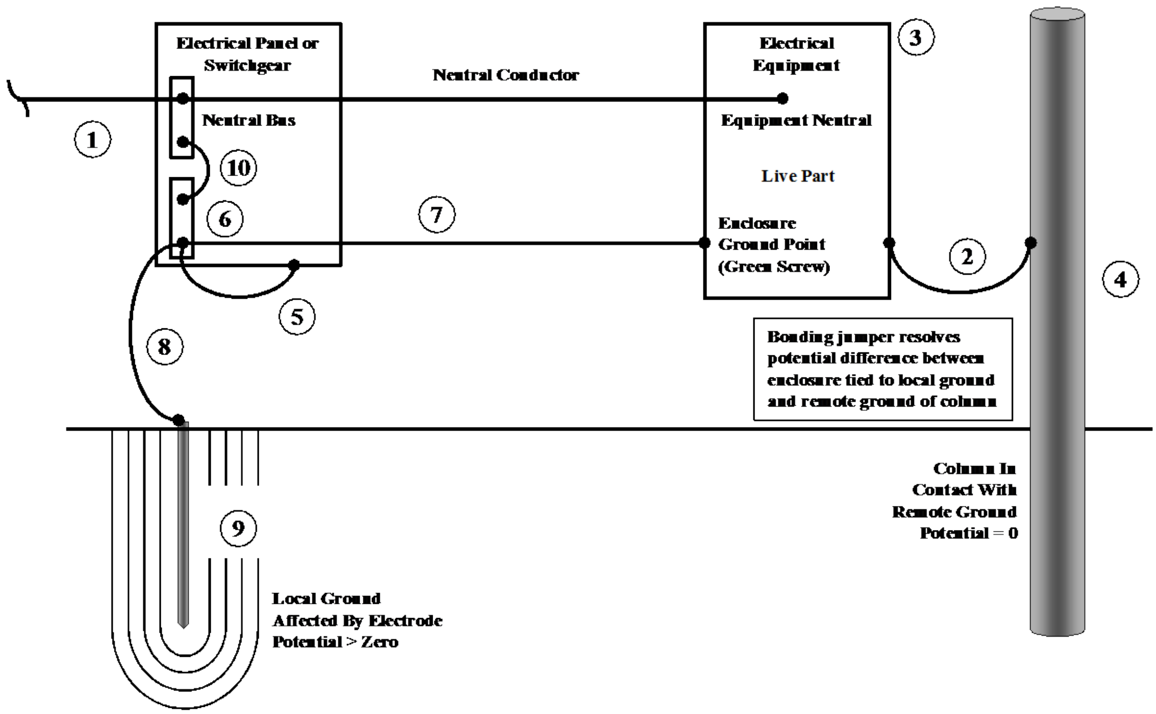


Figure 1—Pictorial representation of service grounding and bonding elements

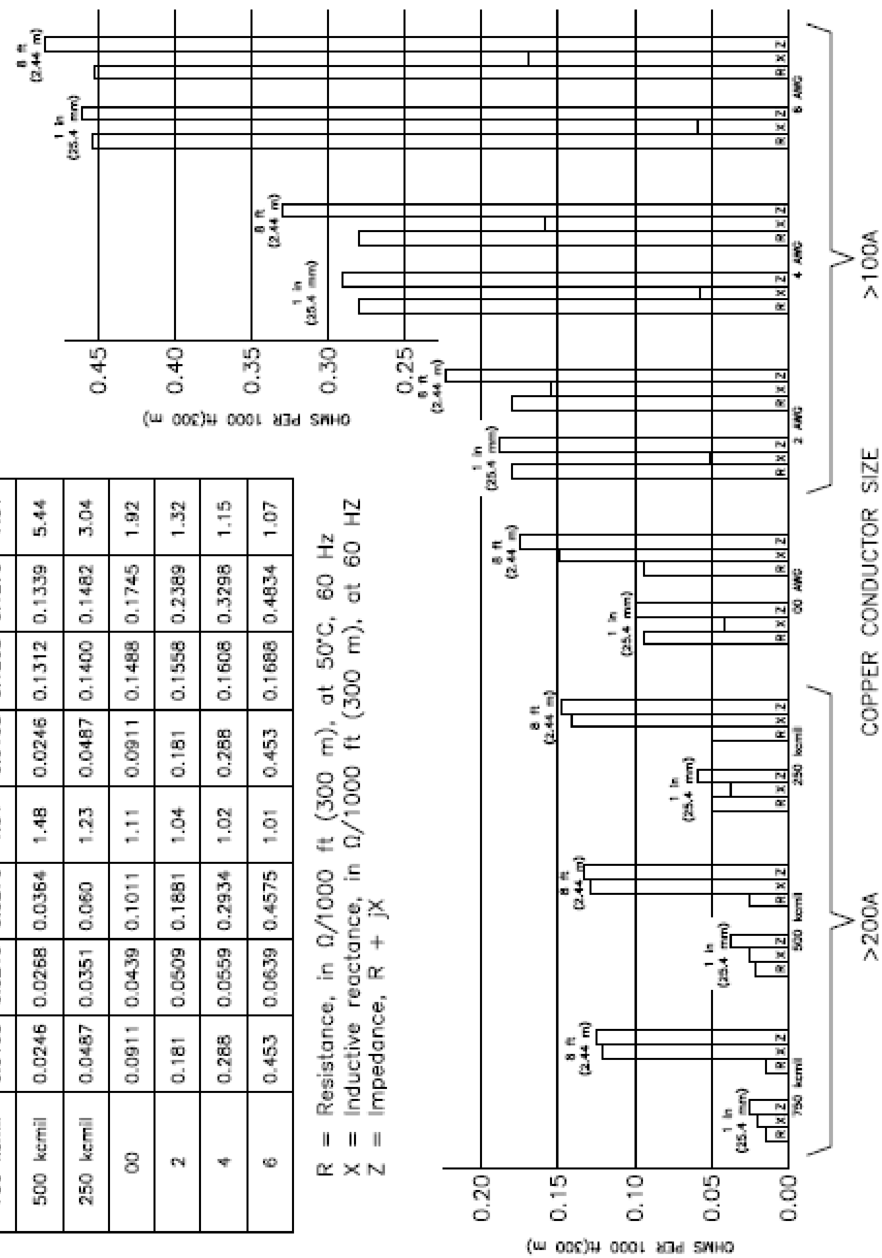
Table 1—Figure 1 tag descriptions per NEC, CEC, or IEC

	NEC	CEC	IEC
1	combined neutral and ground	combined neutral and ground	protective earth neutral (PEN)
2	bonding jumper	bonding jumper	bonding jumper
3	conductive electrical equipment enclosure	conductive electrical equipment enclosure	exposed conductive part
4	building steel, metal fence, metal pipe	building steel, metal fence, metal pipe	extraneous conductive part
5	equipment bonding jumper	equipment bonding jumper	equipment bonding jumper
6	ground bus	ground bus	earthing bus
7	equipment grounding conductor (EGC)	bonding conductor	protective earth conductor (PE)
8	grounding electrode conductor (GEC)	ground conductor	earthing electrode conductor
9	grounding electrode	ground electrode	earth electrode
10	main bonding jumper	main bonding jumper	main bonding jumper
11	neutral or grounded conductor	grounded conductor	neutral conductor

4. Fundamental concepts

For grounding and bonding of ac power systems, the conductor impedance is an important factor. The resistance is primarily a factor of the size and length of the conductor. The reactance is much more complex. The inductance of the conductor is affected by the loop area of the circuit (how close the conductors are to each other) and the proximity of the loop to the source of magnetic flux. Figure 2 provides some typical values of resistance, reactance, and impedance for some common sizes of cable with conductor spacing of 1 in and 8 ft.

To help develop an understanding of the behavior pattern of a single wire as a protective conductor, see Figure 3. A constant current source is assumed with conductor impedance small with respect to the source impedance.



CONDUCTOR SIZE	1 in (25.4 mm) CONDUCTOR SPACING R	X	Z	Z/R	8 ft (2.44 m) CONDUCTOR SPACING R	X	Z	Z/R
750 kcmil	0.0168	0.0219	0.0276	1.64	0.0168	0.1268	0.1279	7.61
500 kcmil	0.0246	0.0268	0.0364	1.48	0.0246	0.1312	0.1339	5.44
250 kcmil	0.0487	0.0351	0.060	1.23	0.0487	0.1400	0.1482	3.04
00	0.0911	0.0439	0.1011	1.11	0.0911	0.1488	0.1745	1.92
2	0.181	0.0509	0.1881	1.04	0.181	0.1558	0.2389	1.32
4	0.288	0.0559	0.2934	1.02	0.288	0.1608	0.3298	1.15
6	0.453	0.0639	0.4575	1.01	0.453	0.1688	0.4834	1.07

R = Resistance, in Ω/1000 ft (300 m), at 50°C, 60 Hz
X = Inductive reactance, in Ω/1000 ft (300 m), at 60 HZ
Z = Impedance, R + jX

Figure 2—Variation of R and X with conductor size and spacings

The protective conductor is considered to be bonded to the supply system neutral conductor, to the building frame, and to the grounding electrode at the source end of the circuit. For the purpose of examining the properties of the protective conductor alone, it will be considered to be installed in metallic conduit and to remain free of any other contact with the building frame throughout its length of 61 m (200 ft). Consider a circuit of 350 A capacity, consisting of 250 mm^2 (500 kcmil) phase conductors and a 100 mm^2 (4/0 AWG) copper protective conductor at 25 °C. It is assumed that the line-to-ground fault current at the outer terminal is 5500 A.

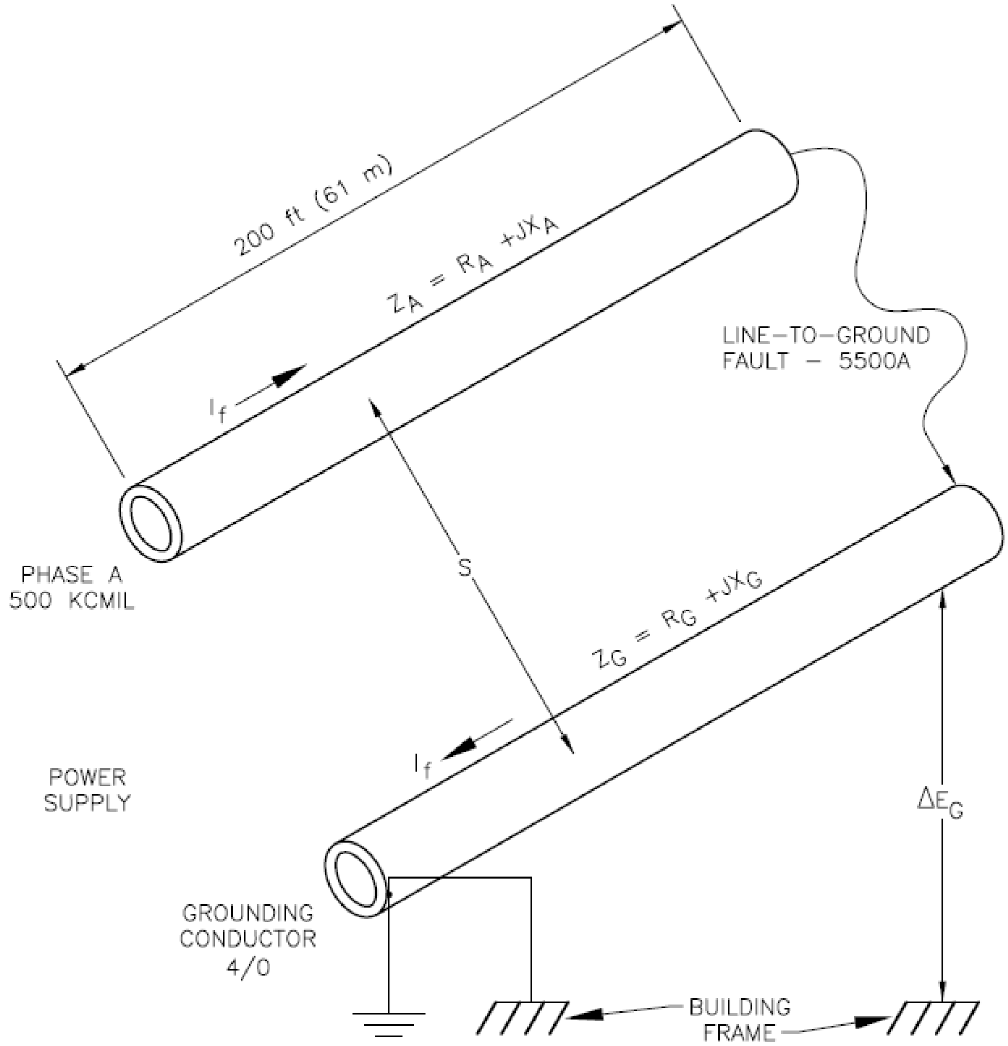


Figure 3—Single wire a protective conductor

Consideration will be given to three values of center-to-center spacing between phase and protective conductors: 51 mm, 203 mm, and 762 mm (2 in, 8 in, and 30 in). The 60 Hz impedance values for phase and protective conductors at 50 °C in ohms for the 61 m (200 ft) run are as shown in Table 2:

Table 2—Impedance as a function of conductor spacing

	Spacing		*R*	*X*	*Z*
	(mm)	(in)	(Ω)	(Ω)	(Ω)
Phase conductor A	51	2	0.0049	0.0085	0.0098
	203	8	0.0049	0.0149	0.0157
	762	30	0.0049	0.0210	0.0216
Protective conductor	51	2	0.0115	0.0108	0.0158
	203	8	0.0115	0.0172	0.0207
	762	30	0.0115	0.0233	0.0260

In Figure 3, the I_f (fault current) × Z_G (ground impedance) = voltage drop along the protective conductor appears as a touch electric shock at the far end of the protective conductor. The line-to-ground fault current

at the outer terminal is assumed to be I_f of 5500 A, the magnitude of shock-voltage exposure for each of the three spacings is shown in Table 3.

Table 3—Shock voltage (E_G) as a function of conductor spacing

Spacing		EG
(mm)	**(in)**	**(V)**
51	2	86.9
203	8	113.9
762	30	143.0

The change in spacing also changes the reactance of the phase conductor (relative to the protective conductor). The corresponding values of the phase-conductor voltage drop (I_f held constant at 5500 A) are shown in Table 4.

A change in the location of the protective conductor changes the value of the reactance in the phase conductor. This fact leads directly to the next important concept. While impedance diagrams display both resistance and reactance as properties of the conductor, the reactance is, in fact, a property of the space electromagnetic field, which encircles the conductor.

Table 4—Phase conductor voltage drop

Spacing		***IZ* drop, phase A**
(mm)	**(in)**	**(V)**
51	2	53.9
203	8	86.4
762	30	118.8

For the conductor geometry shown in Figure 4, the magnetic field, which is responsible for the reactive voltage drop, assumes the character shown in Figure 4. Throughout the space between the two conductors [203 mm (8 in) wide and 60 m (200 ft) long] exists a powerful 60 Hz magnetic field with a driving magnetomotive force of 5500 A turns. This arrangement constitutes a huge electromagnet. That portion of the total magnetic field that encircles the protective conductor is considered to be associated with the reactance of the protective conductor, while that which encircles the phase conductor is considered to be associated with the reactance of the phase conductor.

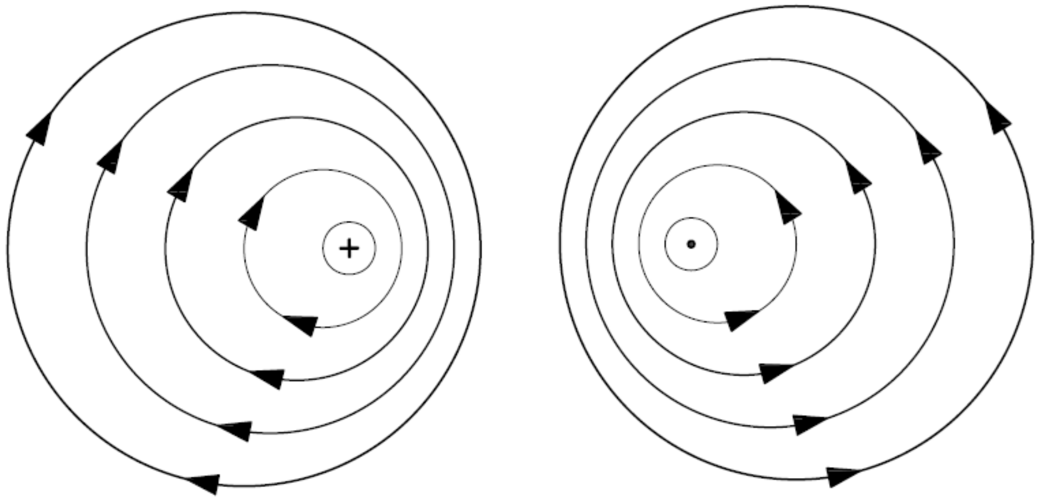


Figure 4—Magnetic field of wire as protective conductor

Any loop of conducting material (wire, pipe, messenger cable, steel structure, etc.) through which some fractional portion of this magnetic field passes will have induced in it a corresponding fractional part of the 60 Hz reactive voltage drop of the main power circuit loop. There need be no physical contact between the two loops. The mutual coupling is entirely magnetic. If the loop in which the voltage is mutually coupled is closed, then instead of a voltage, a circulating current will exist.

Figure 5 shows a possible loop alongside the protective conductor (not the most intensive field strength location). With this loop considered to be open at one corner, the generated voltage therein would be 1.65 V for a 51 mm (2 in) protective conductor spacing, or 5.6 V for a 762 mm (30 in) spacing. If the loop circuit is closed, the flux linkages through this loop will be reduced to near zero, and the induced current will assume the value that becomes necessary to oppose the entrance of flux linkages. In the case illustrated, the induced current might very well be of the order of 500 A.

The situation presented by Figure 5 would not be judged to be a dangerous shock voltage exposure, but the possible arcing and flashing that could occur at a light pressure contact point closing the loop (open-circuit voltage of 2 V−5 V with a closed-circuit current of 500 A) could be a very real source of ignition of combustible material (fire) or of flammable gas (explosion). The same size induction loop around a high capacity outdoor station, where the ground-fault current might be 50 000 A and the spacing between phase and protective conductors 1.8 m (6 ft), might well display an open circuit 60 Hz induced voltage of dangerous shock-hazard magnitude. By constructing a closed loop with no loose connections, so positioned as to block the passage of flux linkages responsible for an objectionable reactance, that reactance can be eliminated.

As far as the shock exposure voltage drop along the protective conductor is concerned, the key factors are protective conductor cross-section area, spacing relative to phase conductors, magnitude of ground-fault current, and circuit length.

In the usual installation, the protective conductor is bonded to the building structure at regular intervals. The first impression is that such bonding causes the shock-exposure voltage to disappear. The correct explanation is that the voltage, which was observed to exist on the protective conductor, has been impressed on the building structure. At the point of bonding, the potential difference has been reduced to zero. At the service equipment, a bonding jumper establishes zero potential difference. Therefore, the voltage drop along the building structure now equals the voltage drop along the protective conductor because the two paths are in parallel. Perhaps voltage differences have been forced to appear between certain building structural members that are more serious than the original one. The problems of determining what voltage differences will appear between designated points of the building have become

considerably more complex. A rational approach to the problem begins with an evaluation of the voltage exposure that would exist with the protective conductor acting alone. This evaluation serves to establish the relative performance quality of the design being studied. It also identifies the maximum voltage difference that could possibly be imparted to the building structure by cross bonding.

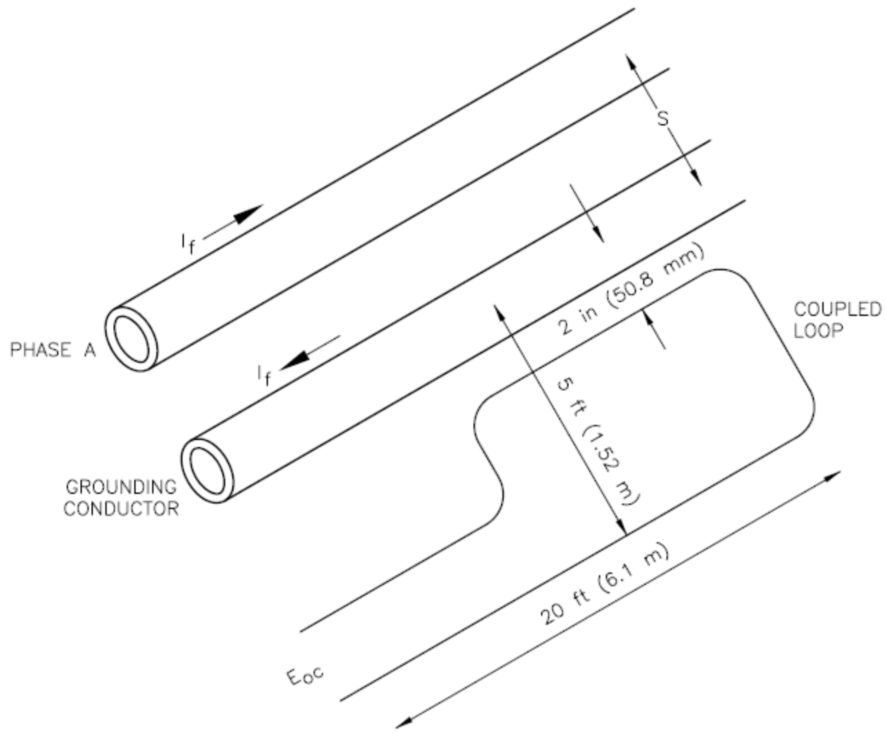


Figure 5—Electromagnetic induction of wire as protective conductor

A bonding connection from a protective conductor to the building frame will result in a reduction of the voltage magnitude along the protective conductor due to the reduction in impedance from the fault point to the source. This reduced impedance will tend to increase the amount of fault current flowing but not in the same proportion as the impedance reduction due to the phase conductor impedance being unaffected.

4.1 Cabling of conductors

Cabling or lacing together all the conductors of one circuit can reduce the spacing between protective and phase conductors to the point of direct contact of the insulation. With other conditions remaining as indicated in Figure 3, the 60 Hz reactances could be reduced to 0.0061 Ω for the protective conductor and to 0.0038 Ω for the phase conductor. While the protective conductor impedance shows little improvement because it is largely resistance limited, the space magnetic field has been substantially reduced, with a corresponding reduction in magnetic coupling to secondary loop circuits.

By distributing the total protective conductor cross section among the interstices of a three-conductor cable (one-third size conductor in each pocket), the effective reactance of the protective conductor can be further reduced, resulting in a corresponding reduction in the space magnetic field strength.

4.2 Enclosing metal shell

By forming the metal of the protective conductor into a tubular shape, within which are run the circuit phase and neutral conductors, a marked improvement in effectiveness is accomplished. The returning ground-fault current distributes itself about the entire enclosing shell in such fashion as to result in a lower round-trip impedance (see Figure 6). The electrical behavior during a line-to-ground fault is that of a coaxial line. Except for the effects of resistivity in the shell, all electric and magnetic fields are contained inside the shell. The external space magnetic field becomes zero.

The customary metal conductor raceway fits this preferred conductor geometry perfectly. It is important that these tubular shaped sections be adequately joined and terminated so that significant additional impedance is not introduced. The normal tubular metal raceway is permitted to serve as the protective conductor.

Practical varieties of metal conductor raceways and metal sheathing possess substantial sheath resistance. The flow of ground-fault current will thus produce a voltage gradient along the protective conductor due to impedance voltage drop. The magnitude of this voltage drop varies widely from one type of grounding method to another. Because of its importance in fixing the magnitude of electric shock voltage exposure, a rather extensive array of tests was conducted to provide specific data. A variety of protective conductor types were examined, covering a range of phase-conductor sizes from 3.3 mm^2 (12 AWG) to 250 mm^2 (500 kcmil). The results are presented in terms of voltage drop along the exterior surface per 1000 A of ground-fault current per 30.5 m (100 ft) of circuit length. The published data (Figure 6 and Table 3) is consolidated in Table 5.

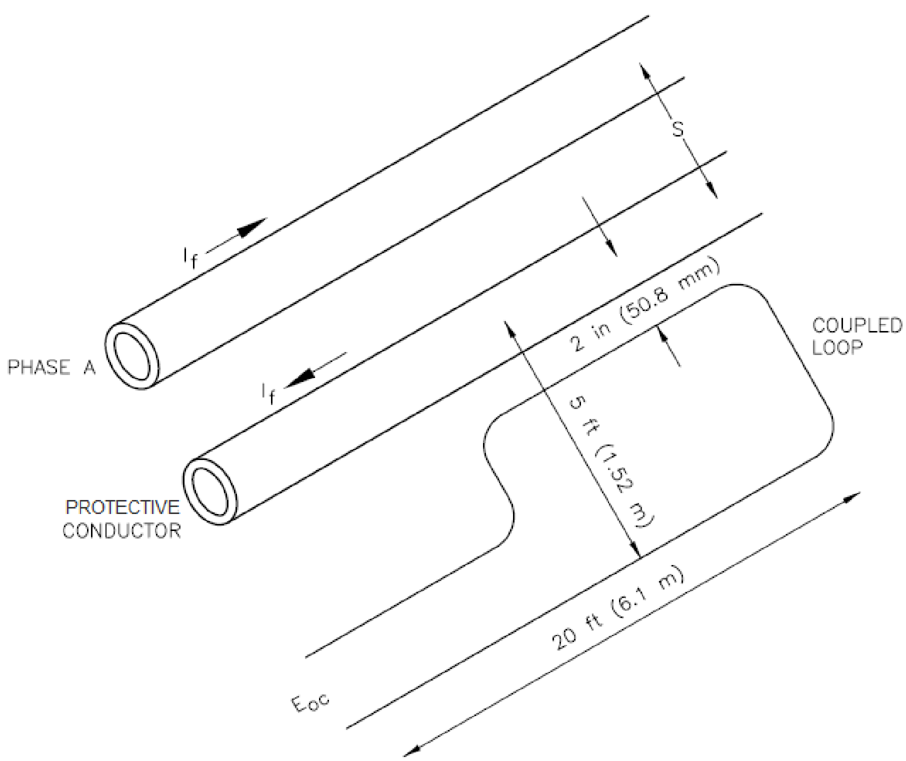


Figure 6—Tubular metal raceway as protective conductor

Table 5—Voltage drop of conductors in cable or conduit

Copper conductor size	Cable or conduit	DC resistance Ω/100 ft	Computed *IR* drop V/1000 A /100 ft	Measured drop[a] V/1000 A /100 ft
500 kcmil	3/C VCI (steel armor)	0.0383	38.3	35
500 kcmil	3/C VCI (steel armor with internal protective conductor)	—	—	5
4/0 AWG	3/C VCI (aluminum armor)[b]	0.286	286	151
4/0 AWG	3/C VCI (aluminum armor with internal protective conductor)[b]	—	—	12
4/0 AWG	3/C VCI (steel armor)	—	—	55
4/0 AWG	3/C VCI (steel armor with internal protective conductor)[b]	—	—	11
4/0 AWG	3/C lead sheath (15 kV)	0.00283	2.83	11
4/0 AWG	4 in rigid steel conduit	0.0025	2.5	1
2/0 AWG	2 in rigid steel conduit	0.0095	9.5	6
1/0 AWG	3/C VCI (steel armor)	0.0458	45.8	51
1/0 AWG	3/C VCI (steel armor with internal protective conductor)[b]	—	—	19
2 AWG	Aluminum sheath (solid sheath M/C cable)	0.01	10.0	9
2 AWG	1 1/4 in rigid steel	0.0108	10.8	11
2 AWG	1 1/4 in EMT	0.0205	20.5	22
2 AWG	1 1/4 in flexible metal conduit (Greenfield)	0.435	435	436
8 AWG	3/4 in rigid steel	0.02	20.0	21
8 AWG	3/4 in EMT	0.0517	51.7	48
8 AWG	3/4 in flexible metal conduit (Greenfield)	1.28	1280	1000
10 AWG	Aluminum sheath (solid sheath M/C cable)	0.015	15.0	16
12 AWG	1/2 in rigid steel	0.0223	22.3	25
12 AWG	1/2 in EMT	0.0706	70.6	70
12 AWG	BX without ground (ac cable)	1.79[c]	1790.0	1543

[a] Value read from bar chart (numeric values not published).
[b] The listing of varnished cambric insulated (VCI) cable is included because it is the only known documented test of aluminum with and without an internal grounding conductor and of the same conductor size comparison of steel vs. aluminum encirclement of conductors.
[c] Does not meet current Underwriters Laboratories listing requirements.

Rigid steel conduit is observed to offer superior performance, principally because of the heavy wall thickness. The striking contrast between steel and aluminum conduit is interesting and offers specific application advantages. The high magnetic permeability of steel should, and does, account for a higher line-to-ground fault impedance. One might assume that the voltage drop along the raceway exterior would also be increased; yet the exact opposite is observed. The effect of the magnetic material in the conduit wall is to confine the return current largely to the internal shell of the conduit, penetrating to the exterior surface only as magnetic saturation in the iron occurs for large fault currents.

Note that the values listed in Table 5 for flexible metal conduit and old-type BX armored cable are excessive. Old-type BX did not incorporate an internal bonding strip in direct contact with the armor. Modern armored cable (Type AC) has such a bonding strip.

Also note that flexible metal conduit (as well as liquid tight flexible metal conduit) that does not have an internal bonding strip is not suitable for equipment grounding and bonding without a separate protective conductor. Short sections of flexible metal conduit, in certain applications, may not be required to have a separate protective conductor, but a separate protective conductor is recommended due to vibration and equipment movement that may loosen the protective connector connection to the flexible conduit.

There is a sharp decrease in voltage drop when an internal protective conductor is added in parallel with the conduit. In addition, the line-to-ground fault impedance will be reduced. Thus, the use of a metallic conduit raceway as a protective conductor, supplemented by a protective conductor within the conduit, achieves both minimum ground fault impedance and minimum shock-hazard voltage.

There is no specific limitation on the length of tubular metal raceway or cable armor that may be used as a protective conductor. Excessive length can result in an impedance that will limit the ability of the circuit overcurrent device to clear a ground fault as well as cause a hazardous voltage on the raceway or cable armor surface. The resulting reduction of impedance when an internal protective conductor is added in parallel with a metal raceway will permit feeder distance to be increased by up to 1.7 times the maximum feeder length without the internal conductor.

For the circuit arrangement indicated in Figure 3, the progressive improvement in shock-voltage exposure with different forms of protective conductors is displayed in Table 2. (The conditions of Figure 3 are maintained, except for protective conductor size and shape. I_f is held constant at 5500 A. The 762 mm (30 in) spacing is included only for reference. This spacing is unlikely in most industrial applications.)

Making the protective conductor a conduit enclosing the phase conductor, the shock-voltage exposure EG drops to 6.7 V for rigid aluminum conduit and to 11 V for rigid steel conduit with the same 5500 A.

The effective performance of an enclosing raceway as a protective conductor should be used to full advantage in electrical system designs. It is important to avoid the use of raceways having inadequate short-time current-carrying capacity unless supplemented with an adequate additional protective conductor run within the raceway. Joints between raceway sections and other grounding and bonding connections should provide good electrical conduction at high fault current levels or the effectiveness of the raceway, as a protective path, will be lost. The value of good workmanship cannot be overestimated.

Not documented in detail is the fact that where more than a single length of conduit was used for a ground return path, sparks were observed at conduit junctions and connections to boxes at the beginning of the experimental measurements. The sparking did not occur during subsequent tests because either the conduit connections or the conduit sections welded to each other by the resultant electrical arcs were made more secure. This result agrees substantially with observations made by many field engineers but not substantiated in current technical literature. The use of a separate EGC, as recommended, installed inside of the metallic conduit, can minimize the probability of arcing at joints and provide maximum fault current for an overcurrent device to clear the fault rapidly.

4.3 Electromagnetic interference suppression

In developing the fundamental behavior patterns of the various forms of protective conductors, the ability to suppress the magnitude of the electric and magnetic fields in the space external to the electric power channel by proper design methods was noted. This knowledge can be employed to make the protective conductor serve to significantly reduce the electrical noise contributed to the space surrounding the electrical run. As might be expected from results so far defined, the enclosing metal raceway is superior to discrete conductors. Tubular steel raceways are very effective in suppressing strong electric fields. High conductance may be needed to achieve very low noise levels.

4.4 Bonding of metal sleeves enclosing a protective conductor

The behavior pattern of an independent protective conductor (such as the run to the grounding electrode at the service or the protective conductor connecting a surge arrestor to an earthing terminal) is very different from that of a power circuit protective conductor (see Figure 7).

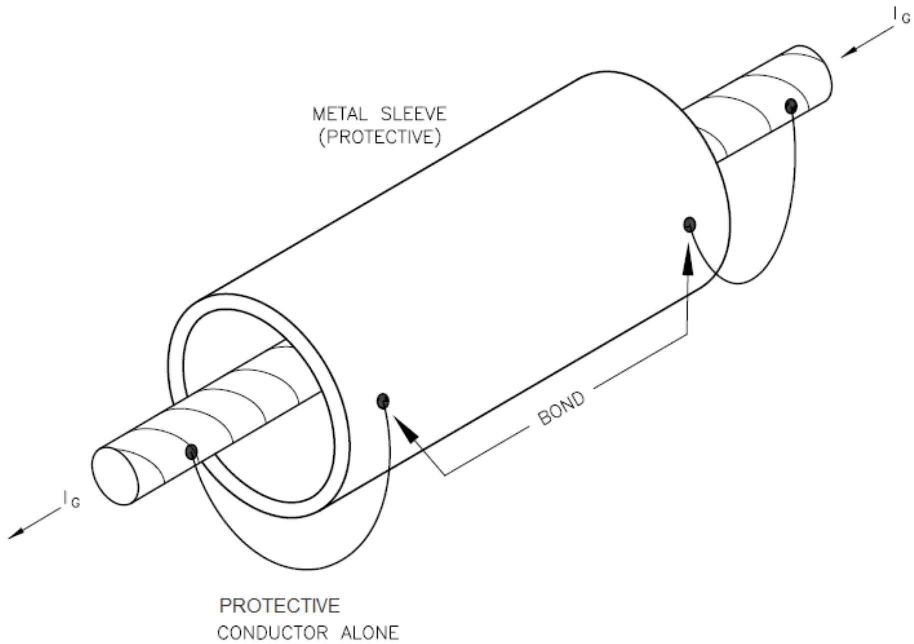


Figure 7—Bonding of metal enclosure

The function in this case is to conduct the one-way current to a ground (earthing) electrode. The return path of this current is remote from the protective conductor. In the case of lightning current, the return path may be so remote as to be obscure. There will be an inductive voltage drop along the conductor length due to a changing current ($L \times di/dt$ or $X_L \times I_{ac}$). The larger the conductor diameter, the lower will be the conductor inductance (or reactance). If the member enclosing the conductor is magnetic, the magnetic field encircling the conductor is increased, which correspondingly increases the inductive voltage drop. If the enclosure is nonmetallic conduit or tubing, there will not be a magnetic effect.

An inductance is commonly made by wrapping a number of turns of conductor wire around a magnetic (iron) core. An equally effective method is to wrap a magnetic (iron) cylinder around a conductor. Such a cylinder is a steel conduit, although even aluminum has an effect from eddy current generated in the conduit. It has been found that enclosing a single protective conductor in steel conduit increases its impedance by a factor of up to 40.

In some cases, installation conditions are such as to warrant the application of a metal enclosure over a section of this type of protective conductor. In all cases where this type of installation is done, the conductor and the enclosing protective metal shell should be bonded together at both ends of every integral section of enclosure for the following reasons:

a) To avoid increased voltage drop if the enclosure is made of magnetic material.
b) To take advantage of the lower voltage drop associated with larger conductor diameter.
c) To permit the steel conduit to carry the major portion of the ground seeking current.

4.5 Protective connections associated with steep wave front voltage protection equipment

The application of surge arresters to transformers (see Figure 8) and surge protective capacitors and arrestors to rotating machines (see Figure 9) illustrates this application of a protective conductor. The function of the protective conductor is to provide a conducting path over which the surge current can be diverted around the apparatus being protected without developing a dangerous voltage magnitude.

In the presence of a changing current (di/dt), there will be an inductive voltage drop developed along the protective conductor itself, which is additive to the protective device voltage. The amount of this added voltage will be proportional to the conductor length and the spacing from the protected apparatus and, of course, to the magnitude of di/dt.

Actual values of di/dt range over wide limits, but a value of 10 kA/μs is representative. With such a rate of rise of current, even 1 μH of inductance can be significant, see Equation (1):

$$E = L \times di/dt \tag{1}$$

$$= 10^{-6} \times 10\,000/10^{-6}$$

$$= 10\,000 \text{ V}$$

NOTE—1 μH is the equivalent of 0.000377 Ω reactance at 60 Hz.

Only a 0.88 m (3 ft) length of 95 mm^2 (4/0 AWG) conductor spaced 1.52 m (5 ft) away from the transformer in Figure 8 would be required to add 10 000 V to the arrester voltage. Thus, protective conductor length and spacing become of paramount importance. One can readily visualize that the additive inductive voltage is generated by the total flux linkages that can be developed through the window between the protective conductor and the protected apparatus.

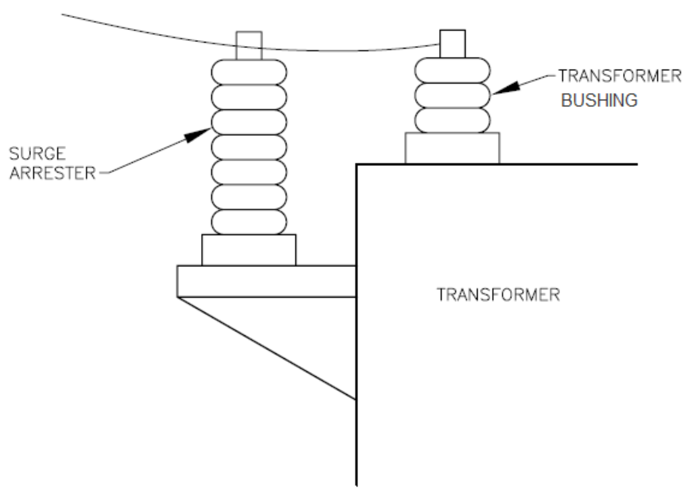
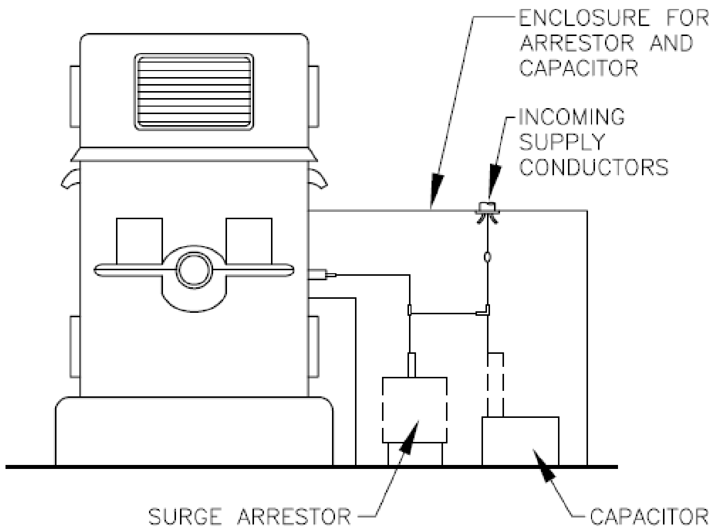


Figure 8—Surge arrestor location on transformer

To take full advantage of the protective properties of the surge arrester in Figure 8, the arrester should be mounted so as to be in direct shunt relationship to the terminal bushings. At lower voltages, an arrester supporting bracket can usually be extended from the base of the bushing. At higher voltages, a shelf extending from the tank body at the proper place to minimize the inductive voltage is often used to support the arresters.

Locating the arrestor at any substantial distance, such as at the pole-top cross arm, with an independent protective conductor can seriously increase the surge voltage stress on a transformer or switchgear by the voltage drop in the arrestor down lead-to-ground. Arresters should be as close as possible to the equipment to be protected and to ground. In low-voltage systems, the same principles dictate that the wiring to the low-voltage SPD be twisted together and be as short as practical.

The same fundamental reasoning applies to the installation geometry of rotating machine surge-protective equipment (see Figure 9). A box, shelf, or bracket directly adjacent to the emerging leads from the machine can accomplish the desired objective.



NOTE—Only one phase shown for clarity

Figure 9—Surge protection equipment on motor

The mounting frame should connect directly with the machine frame to minimize the circuit inductance. The capacitor element of the protection system is the device that deserves prime attention. If this item is properly connected with short, direct connecting leads, the rate of rise of voltage at the motor terminal will be quite gentle, requiring perhaps 10 μs to build up to arrester sparkover value. (For gapless arrestors like varistors, sparkover value equates to voltage at which the device starts conducting.) Thus, the leads to the arrester can be longer because of the modest rate of rise of voltage. In fact, there can be a benefit from inductance in the arrester circuit, which cushions the abrupt drop in machine terminal voltage when the arrester sparks over.

4.6 Connection to earth

The well-established usage of the terms ground and earth in the technical literature leads to many misconceptions, since they seemingly are almost alike, yet in fact are not. The electrical system of an aircraft in flight will have a ground bus, protective conductors, etc. To suggest that ground and earth can be used interchangeably is obviously in error here. To an electrician working on the tenth floor of a modern steel-structured building, the referenced ground is the building frame, attached metal equipment, and the electrical system of protective conductors present at the working area. What might be the potential of earth is of negligible importance to this worker on the tenth floor.

If the worker is transported to the building basement in which the concrete floor slab rests on soil, or to the yard area of an outdoor open-frame substation, earth does become the proper reference ground to which electric-shock-voltage exposure should be referenced.

Thus, the proper reference ground to be used in expressing voltage exposure magnitudes may sometimes be earth, but (outside of the outdoor substation area) most likely will be the electric circuit metallic protective conductor. The following paragraphs will show that the potential of earth may be greatly different from that

of the protective conductor. It therefore becomes very important that shock-exposure voltages be expressed relative to the proper reference ground.

All electrical systems, even those installed in airborne vehicles, may be faced with circumstances in which sources of electric current are seeking a path to ground. These conditions can do serious damage to electrical equipment or develop dangerous electric-shock-hazard exposure to persons in the area, unless this stray current is diverted to a preplanned path to a ground of adequate capability.

A comprehensive treatment of the behavior of earthing terminals appears in IEEE Std 80. The prime purpose of this discussion is to develop a concept of the potential gradients created in discharging current into earth and the manner in which the equipment grounding and bonding problem is thereby influenced.

Earth is inherently a rather poor conductor whose resistivity is around one billion times that of copper. A 3 m (10 ft) long by 16 mm (5/8 in) diameter ground rod driven into earth might very likely represent a 25 Ω connection to earth. This resistance may be imagined to be made up of the collective resistance of a series of equal thickness concentric cylindrical shells of earth. The inner shell will, of course, represent the largest incremental value of resistance since the resistance is inversely proportional to the shell diameter. Thus, the central small diameter shells of earth constitute the bulk of the earthing terminal resistance. Half of the 25 Ω resistance value would likely be contained within a 0.3 m (1 ft) diameter cylinder.

For the same reason, half of the voltage drop resulting from current injection into this grounding electrode would appear across the first 0.15 m (0.5 ft) of earth surface radially away from the ground rod. If a current of 1000 A were forced into this grounding electrode, the rod would be forced to rise above mean earth potential by 25 000 V (1000 A × 25 Ω). Half of this voltage (12 500 V) would appear as a voltage drop between the rod and the earth spaced only 0.15 m (0.5 ft) away from the rod. While this current is flowing, a person standing on earth 0.15 m (0.5 ft) away from the ground rod and touching the connecting lead to the electrode would be spanning a potential difference of 12 500 V. A three-dimensional plot of earth surface potential vs. distance from the ground rod would create the anthill-shape displayed in Figure 10. This is related to electrode resistance versus radius from electrode as shown in Table 6. The central peak value would be the rod potential (referred to remote earth potential), namely 25 000 V. Moving away from the rod in any horizontal direction would rapidly reduce the voltage value. The half-voltage contour would be a horizontal circle 0.3 m (1 ft) in diameter encircling the rod.

For example, consider a 15 m × 15 m (50 ft × 50 ft) substation area within which 25 driven rods, each of the type previously described, had been uniformly distributed. Because of the overlapping potential gradient patterns, the composite resistance will not be as low as 25 Ω. For the case at hand, a 2 Ω value would be typical. Should a line-to-ground fault at this station produce a 10 000 A discharge into the earthing terminal, the resulting voltage contour map would display 25 sharp-pointed potential mounds peaking at 20 000 V. In between would be dish-shaped voltage contours with minimum values ranging from perhaps 2000 V to 5000 V, depending on location.

Such a highly variable voltage contour pattern within the walking area of the substation would not be acceptable. Additional shallow buried ground wires can be employed to elevate the earth surface potential between main electrodes (see IEEE Std 80). Note particularly the concepts of step, touch, and transferred potentials. Additional shallow buried grounding wires can be employed to tailor the voltage contour adjacent to, but external to, the enclosing fence. Beds of coarse cracked rock, well drained to prevent standing water, can contribute to improved electric shock security. Metal grill mats bonded to the steel-framework supporting switch operating handles and located at the standing location of switch operators can ensure that the operator's hands and feet are referenced to the same potential.

5. Equipment grounding and bonding as influenced by type of use

The principal classes of use may be categorized for our purposes as follows:

a) Outdoor open frame substations

b) Outdoor unit substations

c) Outdoor portable heavy-duty equipment, such as shovels, draglines, dredges

d) Interior wiring systems

e) Interior unity substations and switching centers

The problems presented to the equipment grounding and bonding system designer vary quite widely with the different classes of use. The basic objectives remain the same throughout. The equipment grounding and bonding system should cope with the current flow (magnitude and duration) that is imposed on it by extraordinary events that occur during the course of ordinary power system operation. This duty is most commonly the result of an insulation failure between an energized conductor and the conductive metallic structure that supports or encloses it. However, the duty may result from an outside injection of current, such as a lightning discharge or a falling overhead high-voltage conductor. The equipment grounding and bonding system is expected to carry this imposed current without thermal distress and without creating dangerous electric shock voltage exposure to persons in the area.

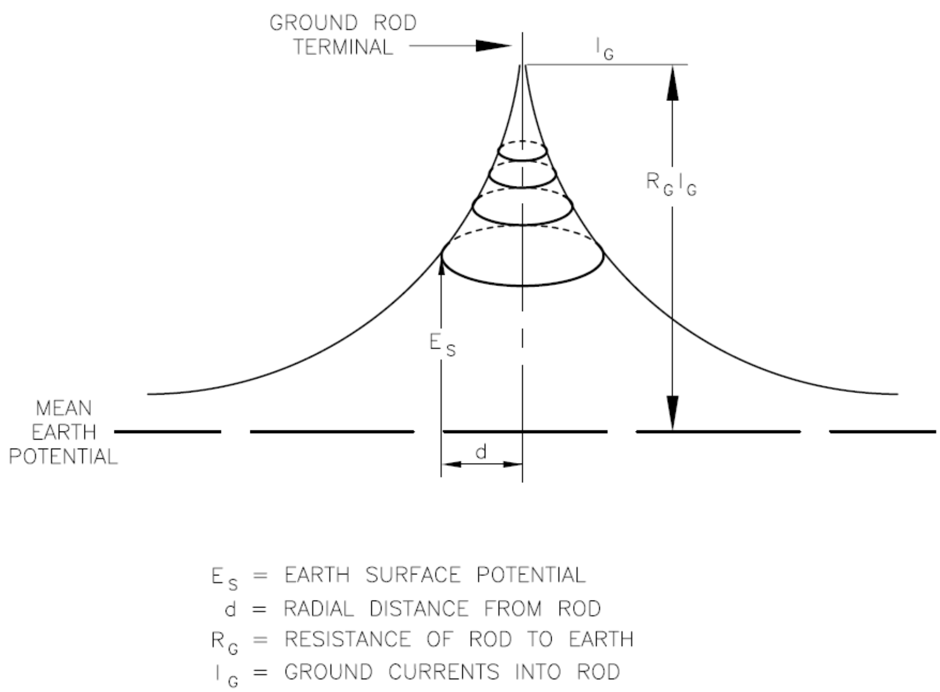


Figure 10—Earth surface potential around ground rod during current flow

Table 6—Ground electrode resistance

Electrode resistance at a radius r ft from a 3 m (10 ft) long × 15.88 mm (5/8 in) diameter rod (where total resistance at r = 7.6 m (25 ft) = 100%)		
Distance from electrode surface (r) resistance		**Approximate percentage of total resistance**
ft	**m**	
0.1	0.03	25
0.2	0.06	38
0.3	0.09	46
0.5	0.15	52
1.0	0.3	68
5.0	1.5	86
10.0	3.0	94
15.0	4.6	97
20.0	6.1	99
25.0	7.6	100
(100.0)[a]	30.5	(104)
(1000.0)[a]	305.0	(117)

[a]These figures show that for the most practical reasons, the majority of the resistance to remote earth occurs within 7.6 m (25 ft) of the electrode, i.e., at 1000 ft the resistance is only 17% higher than that of 7.6 m (25 ft).

6. Outdoor open-frame substations

6.1 General

The distributed nature of the typical outdoor open-frame substation presents some of the most perplexing equipment grounding and bonding problems to be found anywhere. Having various pieces of major apparatus appear as island installations within the substation area is common. For any single equipment item, the voltage stress imposed on its insulation system will be determined by the voltage difference between its electrical terminals and the frame or metal case that encloses its active parts. The magnitude of electric-shock exposure to an operating or maintenance person within the substation area proper will be a function of the voltage difference between the ground surface on which this person stands and the metal that the person normally touches, such as apparatus frames or substation structure.

The magnitude of electric-shock voltage exposure to a person approaching the enclosing fence will depend on the character of the earth surface voltage gradient contours adjacent to the fence on the outside of the substation area.

Connecting a protective conductor to electrical equipment enclosures, or even fences, does not ensure that hazardous shock voltages will not be present. Adjacent ground surfaces may have steep voltage gradients within reach of the equipment unless controlled or mitigated by insulating coverings of ground, such as crushed rock or asphalt, and proper design of a ground grid. The grid also functions to preserve an equipotential plane in the vicinity of grounded metal enclosures or structures, and this function is a standard criterion of the grid design.

6.2 Design of paths for power frequency ground-fault current flow

This ability to carry the ground-fault current from the point where it enters the station to the point where it is to depart is accomplished by supplementing the inherent metallic substation structure with an array of protective conductors that interconnect the bases of structural columns and are extended to the island installations of apparatus, routed over appropriate paths. Copper wire is generally used for this purpose, with the conductor size ranging from 70 mm^2 (2/0 AWG) for small stations, for instance, to

perhaps 240 mm^2 (500 kcmil) for large stations. It is appropriate to seek an effective short-time current capability in the protective conductor path that is no less than 25% of that possessed by the phase conductor with which it is associated. In any case, it should be capable of accepting the line-to-ground short-circuit current (magnitude and duration) permitted to flow by the overcurrent protection system without thermal distress.

The routing of a protective conductor should seek to minimize the separation distance between it and the associated phase conductors. In multibay metal structure construction, the short-circuited loops created by the bonding of protective conductors between column bases may effectively limit the ground-circuit reactance under seemingly wide spacing conditions.

Protective conductors sized and routed according to the same rules should be run to those points required for system grounding connections, such as to the neutral terminal of a power transformer that is to be grounded or to the neutral of a grounding transformer.

Junctions between sections of wire protective conductors should be made by exothermic welding or connectors approved for the purpose. At the terminations, exothermic welding or fittings approved for the purpose should be used.

If overhead-line ground conductors are terminated at towers along the substation outer boundary and the phase conductors continue out across the station plot, perhaps to a point where they drop down to apparatus terminals, an adequately sized protective conductor should be strung across the area with a vertical down member to the apparatus frame to establish a path for ground current flow that remains reasonably close to the route of the phase conductors.

It is important that the protective conductor system extend to and connect with each of the island structures contained within the substation area.

6.3 Design of earthing connections

The achievement of a prescribed degree of connection to earth will constitute an important design objective. This achievement will usually involve a multiplicity of earthing connections (grounding electrodes) distributed about the substation area. If individual grounding electrodes are not kept sufficiently separated physically, their effectiveness is severely impaired.

One specific design limit may be the maximum allowable voltage excursion on the substation structure (relative to mean earth potential) due to a line-to-ground power system fault or a lightning discharge. All signal and communication circuits that extend from this station to remote locations should be designed to accommodate this voltage excursion without damage. The allowable voltage excursion on the station structure may be limited by the voltage rating of a power circuit entering the station. Consider, for instance, a station whose main circuits operate at 230 kV, but which contains outgoing circuits operating at 4.16 kV. A voltage excursion on the station ground mat of 25 kV would not be troublesome to the 230 kV system but would be disastrous to components of the 4.16 kV system. Even the best of available surge arresters on the 4.16 kV circuits would be to no avail. The excess seal-off voltage present would promptly result in their destruction. The allowable maximum voltage excursion on the station ground mat may be set by one of a variety of factors. Once the allowable maximum voltage is set, the design of the station grounding systems can proceed.

Reinforcing steel located in below-grade foundation footings is effective as functional grounding electrodes. All future station design specifications should call for electrical bonding between the metal tower base plate and the reinforcing bars in buried concrete footings. This bonding can be accomplished readily in most instances via the hold-down J bolts, provided that the bolts are bonded to the reinforcing bars.

If the soil at the substation site tends to be an active electrolyte-like cinder fill, the use of dissimilar metals (for instance, copper and steel) as grounding electrodes bonded together in the station-grounding network may lead to objectionable electrolytic deterioration of the buried steel members. With today's knowledge, the avoidance of such trouble may be relatively easy. When the soil is active with a resistivity less than 2000 ohm-cm, the required earthing connection may be obtained using only the buried steel members forming an inherent part of the station. If the soil is not active, the intermix of metals such as copper and steel is not troublesome.

Lightning masts extending upward from the top structural members of the station can be effective in intercepting lightning strokes and leading the discharged current to earth without insulation flashover at the station. The avoidance of insulation flashover is aided by higher insulation flashover levels at the station and opposed by more intense lightning strokes. However, an installation that reduces the number of flashover incidents by 60% (far short of perfection) can still be a sound economic investment.

6.4 Surge voltage protective equipment

Surge voltage protective devices intended to deal effectively with fast-front voltage transients should be connected in a close shunt relationship to the apparatus being protected.

The presence of an exposed overhead line running to the station, but terminating at an open switch or open circuit breaker, invites a flashover at the open terminal because of the tendency for a traveling voltage wave to double its voltage upon encountering an open terminal. The possibility of such an event and its consequences should receive deliberate consideration. If found to be likely and objectionable, this type of flashover can be prevented by the installation of line-type surge arresters directly ahead of the open circuit point on the circuit or by over-insulation (double normal value of the approaching line) of the terminal end of the line within the confines of the station, ahead of the point of open circuit. Both sides of an open switch may need surge arrester protection if there is lightning exposure on both sides.

NOTE—The need for increased withstand voltage also applies to the circuit-opening switching device.

6.5 Control of surface voltage gradient

The tendency for steeply rising voltage gradients to appear directly around discrete grounding electrodes results in a very non-uniform ground surface potential in the substation area during a ground fault incident. This non-uniformity can appear as a dangerous electric-shock voltage exposure to the persons working in the substation area (see IEEE Std 80). Designing for a maximum voltage excursion on the station structure low enough to avoid danger is hardly reasonable. The alternative approach is to employ a mesh grid of relatively small bare conductors located slightly below grade and connected to the station frame. Although this alternative approach is unlikely to reduce the overall station earthing resistance by very much, it will function (like conducting tape on cable insulation) to bring all parts of the substation surface earth lying above the grid mesh to nearly the same potential as the metal grid (that of the substation metal structure). Only small scallops of lesser voltage magnitude will exist between the crisscross conductors of the grid mesh. The possible magnitude of electric-shock voltage exposure to maintenance personnel due to earth surface gradients can be reduced to tolerable levels. A surface layer of coarse crushed non-conductive rock is commonly employed to contribute to increased contact resistance between the yard surface and the worker's feet.

6.6 Voltage gradients external to, but adjacent to, the boundary fence

The steepness of the surface voltage contour adjacent to but outside the enclosing fence determines whether a person approaching the fence and touching it to the limit of their reach could receive a dangerous electric

shock. If the fence were allowed to float, the adjacent voltage gradient would be substantially reduced. Common practice is to bond the fence to the station ground mat, which will take it up to the full mat potential and create a high surface gradient adjacent to the fence. In defense of the practice of bonding the fence to the station ground mat is the added security afforded should a high-voltage line conductor break and fall on the fence. The bond to the station ground allows the entire station grounding system to participate in holding down the voltage magnitude of the fence and avoiding ground fault impedance that might otherwise impede the performance of ground overcurrent relaying. Operating the enclosing fence at station ground mat potential also improves the uniformity of surface gradient within the substation area.

An inviting alternative would locate the boundary fence along a specific voltage contour line (or design for a constant voltage contour along the desired route of the fence). This approach might easily result in a 50% reduction in earth surface potentials external to the fence. To minimize the danger of increased voltage exposure from a broken line conductor, suitable guards would be needed to prevent a falling energized line conductor from making physical contact with the fence. Although inviting, this approach is not practical due to the unknowns of soil strata that make the contours impossible to predict.

The present trend seems to favor a solid bond between the boundary fence and the station ground mat. A conductor is buried below grade adjacent to the fence on the outside of the substation area to control the step and touch potential exposure to acceptable values (see IEEE Std 80).

It is very important to avoid a metallic extension from the station structure to some point outside the fenced area, which is exposed to contact by persons or animals. Such an extension might take the form of a water pipe, an air pipe, a messenger cable, metal fence etc., seemingly having no electrical function. What the extension does is convey the potential of the station ground mat to the far end of the metal extension. The earth surface potential drops off fairly rapidly as one moves away from the boundary fence. The 50% voltage contour will be reached in a short distance away from a small station and in a longer separation distance from a large station. Even a fairly large station will display a 50% drop-off in surface potential within 3 m (10 ft). Thus, it would be entirely possible for a person standing on earth and touching a pipe extension from the station structure only 3 m (10 ft) removed from the enclosing fence to be subject to an electric shock voltage of 50% of the ground mat voltage of the station. A station ground mat voltage of 5000 V is not at all unusual for stations operating in the 4.16 kV to 33 kV range.

7. Unit substations

While the functional objectives remain unchanged, the concentration of apparatus items into a single metal-enclosed package greatly simplifies the equipment grounding and bonding system plan. Even the presence of a single separate line-terminating structure adds little complexity.

The protective conductor associated with each electric circuit to and from the substation is continued to the substation proper and terminated on the ground bus provided there. This conductor should be of the prescribed cross section for the capacity of circuit involved and should be run with as close physical spacing to the power conductors as is feasible.

The problem of avoiding dangerous electric-shock voltage exposure to persons in proximity to the enclosing fence involves the same considerations as in the case of open frame substations. Within the confines of many industrial plants, impedance grounding (either low or high) is used to limit the level of ground-fault current (400 A being a common value for low-impedance grounding). This reduces the voltage gradients around the substation so that no fenced enclosure is needed. Persons can be permitted to approach and touch the substation enclosure with minimal risk of dangerous electric-shock exposure. Of course, the ground bus and enclosure frame of the substation should be connected to the building grounding and bonding system, whether or not a local grounding electrode system is installed.

If the substation structure is exposed to lightning or contains surge arresters, the installation should include an appropriate grounding electrode. The reinforcing bars contained on the below-grade foundation structure will usually provide this function adequately.

8. Interior wiring systems

8.1 General

All equipment grounding and bonding system designs for installation within buildings of the types named should recognize and conform to the minimum requirements contained in the local codes and standards. Code designated minimum acceptable limits may not be adequate for a particular application and may not necessarily provide for the efficient or practical use of high technology utilization equipment. The minimum requirements should be expanded in a more conservative direction as far as the system designer considers appropriate based on specific project and site conditions and in accordance with the recommendations of this recommended practice.

8.2 Service equipment

The term service equipment applies to the switching and protective equipment installed where the electric power from the utility is considered to enter the building, structure, or site. The required installation practices and protective equipment employed at and downstream of the service equipment are designed to ensure an electric power system that will not create fire or explosion hazards, dangerous electric-shock voltage exposure to occupants, or an unfavorable electrical ambient condition within buildings. The electric power conductors from the utility that delivers power to the establishment, the service entrance conductors, do not enjoy the quality of protection afforded all circuits extending beyond the service equipment. An electric fault in these conductors may create a severe arcing fault that may persist for an extended interval and represent a dangerous source of fire ignition. Code recommendations typically make clear the intent that all grounding electrodes, including external water piping and effectively grounded metal building frames, be bonded to the equipment grounding and bonding system at the building supply equipment. Further, all other electrical services that contain metallic conductors (e.g., telephone, cable, data) need to be connected to the equipment grounding and bonding system at the building service entrance to prevent differences in ground potentials between the various systems.

The intended overall purpose of the grounding and bonding rules is to achieve, as nearly as practical, a zero potential difference condition between electrical protective conductors, the frames of electrical equipment, metal raceways that enclose electrical conductors, and the various items of exposed metal building frames and metal piping within the building. To any person within the building, this absence of electric-shock voltage exposure continues unchanged, even though the grounded electric service conductor assumes a substantial voltage deviation from mean earth potential.

The creation of voltage differences between these designated exposed metal parts within the building will be the result of unplanned, unwanted current flow through these conducting members, usually as a result of an insulation failure on an energized power conductor.

8.3 Interior electric circuits

With every electric power circuit extending from the service equipment or building supply equipment into the building interior supplying electric power to equipment or apparatus that should be grounded, a protective conductor should be run with the power conductors. In most cases, the metal conductor

enclosure (e.g., tubular metal raceway or cable armor) or cable tray itself is permitted to serve as the protective conductor. The equipment and apparatus requirement for grounding is accomplished by an electrical bond between the frame (or structure) of such equipment (or apparatus) and the protective conductor run with that electric circuit. The protective conductor is not intended to carry nor should it be connected to carry any normal-load current. Thus, the protective conductor maintains the desired zero potential difference concept throughout the extent of the protective conductor harness. Only when unplanned, unwanted fault currents flow along these conductors will there be observed voltage differences.

8.4 Thermal withstand

8.4.1 General

When metallic conduit is used as a protective conductor, no special considerations are necessary for fault duty of the conduit. When a copper conductor is used to supplement the metallic conduit or where a conductor is necessary, such as in nonmetallic conduit, the design should be evaluated to ensure that the conductor thermal rating is not exceeded. Exceeding the thermal rating can have two effects:

a) Increased temperature can damage the insulation either of the protective conductor in case it is insulated or of adjacent phase conductors, especially when the protective conductor is bare, rendering them unusable following fault clearing.
b) Excessive temperature can fuse the protective conductor, clearing the fault current path but rendering faulted equipment unsafe due to elevated voltages.

Thermal stress is expressed in terms of I^2t where I is the rms fault current and t is the time to clear the fault. Thermal stress can be excessive due to high current or to long clearing time.

8.4.2 Insulation damage

Damage to thermoplastic, cross-linked polyethylene, and ethylene propylene rubber insulation is defined by Equation (2) for copper conductors and Equation (3) for aluminum conductors:

$$\left(\frac{I^2}{A^2}\right)t = 0.0297 \log_{10}\left[\frac{T_m + 234}{T_i + 234}\right] \quad (2)$$

$$\left(\frac{I^2}{A^2}\right)t = 0.0125 \log_{10}\left[\frac{T_m + 228}{T_i + 228}\right] \quad (3)$$

where

I = fault current through conductor in amperes

A = conductor cross-sectional area in circular mils

t = time of fault in seconds

T_i = initial operating temperature in degrees Celsius

T_m = maximum temperature for no damage in degrees Celsius

The initial temperature, T_i, is often taken as the conductor maximum operating temperature rating rather than the actual operating temperature. This is a conservative approach but may result in conductor oversizing by one trade size.

The maximum temperature, T_m, is given as 150 °C for thermoplastic insulation and 250 °C for cross-linked polyethylene and ethylene propylene rubber insulation. If the protective conductor is undersized for the fault current and the clearing time, insulation damage to phase conductors in a conduit may occur due to the proximity of the protective conductor to the phase conductor. If fusing is a criterion, then a final temperature of 1000 °C for copper and 630 °C for aluminum may be used.

8.4.3 Automatic interrupting devices

All automatic interrupting devices, whether fuse or circuit breaker, require a definite time to accomplish current interruption. Most devices are inverse time in that the clearing time is less if the current is higher. Each device, though, has an upper limit of maximum speed of clearing determined by physical considerations of mass and energy.

Three-phase circuit breakers often have adjustable time-current characteristics. In the simplest form, the phase overcurrent sensing magnetic or solid-state pickup for instantaneous operation may be adjusted from about 300% to 500% of overcurrent rating at the low end to about 800% to 1000% of overcurrent rating at the high end. If the ground-fault circuit is designed for a minimum of 500% of overcurrent rating, then a high pickup could result in a long response time and considerable damage, especially for an arcing ground fault. There is a tendency to set the instantaneous phase overcurrent pickup, whether magnetic or solid-state, as high as possible to avoid nuisance tripping due to high initial inrush currents. This practice is not recommended, as the overcurrent device may then not be capable of protecting the protective conductor within its short-circuit rating. The attempted use of a 1000 A or greater overcurrent protective device on a 480/277 V solidly grounded wye system to protect for arcing ground faults is a misapplication of the phase overcurrent protective device. More sophisticated circuit-breaker trip devices may have adjustable time delays that permit shaping the time-current curve to coordinate with both upstream and downstream devices. There is a tendency to set the time delay as long as possible to achieve coordination with as many downstream overcurrent protective devices as possible. Setting of high-current pickup to excessively high values or increasing time delays to high values could cause thermal damage in the protective conductor.

There are several methods available that allow for both selective coordination and adequate protection of system components, including the ground return path. These methods include zone selective interlocking and differential relaying. Both methods allow for immediate tripping when the fault is within the device's zone of protection.

8.4.4 Protective conductor sizing

EGCs should be sized to provide adequate fault current to ensure operation of the circuit protective device. Local code recommendations for a minimum size protective conductor should be recognized as the minimum size conductor that may be used, with no endorsement of adequacy. The conductor should have the adequate capacity to safely conduct any fault current imposed upon it, to have sufficiently low impedance limiting the voltage to ground during faults, and to facilitate the operation of the overcurrent protective devices, even if the conductor must be sized larger than given in the table. A protective conductor installed in a metallic raceway and considered to be supplementary or redundant to the conduit should be sized in the same manner without consideration for the presence of the metallic raceway. The user should note that the typical local code recommendations cover the sizing of protective conductors of the wire type.

Selection of a protective conductor sized in accordance with the regulatory standards will not necessarily provide a system that is free from potential insulation damage for extreme fault levels or events such as a

lightning strike. Where a separate protective conductor is used to supplement a metallic conduit grounding and bonding system, determining the division of fault current between the conductor and the conduit is difficult. It is possible that past ground faults in metallic conduit systems have not caused thermal damage because the maximum ground-fault current did not flow through the conductor.

The preceding considerations do not hold for protective conductors in nonmetallic conduit. In this case, all the ground-fault current will flow in the protective conductor and thermal damage should be considered. As an example, consider a 400 A feeder with a 3 AWG protective conductor. Using an initial temperature of 60 °C and a final temperature of 250 °C for cross-linked polyethylene insulation, $I^2t = 17.8 \times 106$. If the ground-fault current is designed to be a minimum of 500% of rated current, then the protective device should clear the fault within 4.5 s in order to limit the final temperature to less than 250 °C. Design of the ground-fault current to be a minimum of 800% of rated current will reduce the protective device required clearing time to 1.7 s.

At 500% of rated current, many overcurrent protective devices, both fuse and circuit breaker, will not clear for over a half minute at their maximum setting. Thus, it is important that the specific overcurrent device be a part of the protective conductor circuit design, using the maximum available time delay of an adjustable breaker as criteria. Choosing the appropriate size of the protective conductor will permit standard overcurrent devices to adequately protect the protective conductors from thermal damage. Such standard devices are normally applied because of availability and their need to achieve system coordination. Faster acting overcurrent devices or ground-fault sensing equipment may be used to protect an existing protective conductor, but they will normally increase equipment costs and degrade system performance.

9. Interior unit substations and switching centers

9.1 Switching centers

Switching centers of modern vintage will for the most part consist of integral factory-designed metal-enclosed equipment. All internal components will be prepositioned to meet the applicable industry standards. Within this structure, the requirements for protective conductors will have been recognized and supposedly provided for. With the knowledge that ground-fault current will seek a path in close physical proximity to the phase conductor that carries this current in the outgoing direction, it is appropriate to make a casual inspection to confirm that these requirements have been properly recognized.

The field installation problem boils down to a very simple one of assuring the integrity of the protective conductors. Attention should be given to the proper termination of the protective conductor associated with each circuit entering the equipment. The protective conductor should meet the cross-section requirements of that circuit. The physical routing should meet the objectives previously named. The terminating fittings should meet the requirements of an electrical junction expected to safely accommodate the high-magnitude short-time current flow. The terminating point on the switching structure should reflect the same capability.

One of the most neglected spots is the termination of a metal raceway when it is used as the protective conductor. Commonly, the switching structure contains no metal floor plate. The raceways, typically metal conduits, have been stubbed up through a concrete floor so as to terminate within the open floor area inside the boundaries set by the vertical side sheets of the equipment. The following two protective conductor errors appear quite often:

a) The metal raceways or cable trays are not recognized as an electrical conductor (the protective conductor), and no connection is made to the stub end extending into the equipment enclosure.

b) The bonding lead from the raceway is thought to be needed only as a static drain and is connected to the ground bus with only a 4 mm^2 (12 AWG) conductor.

Metal raceways that serve as the protective conductor and terminate at the side sheets or cover plate of the equipment enclosure should be made up tight with double locknuts and supplemented with a bonding

jumper. Proper termination of the raceway system to the equipment enclosure can prevent burnouts at the connection of sheet metal panels to each other with bolts or sheet metal screws, which minimize the risk of serious damage to the equipment and injury to personnel.

9.2 Unit substations

Unit substations present some additional problems. The electrical system derived from the transformer secondary represents a new electrical system with its own equipment grounding and bonding system requirements.

The treatment of all primary circuits entering the structural housing should be designed with the same criteria used for a simple switching structure. A protective conductor running back to the source of primary power is required in case of a circuit fault-to-ground at any point along the primary circuits, within the enclosure containing the step-down transformer, within the primary circuit switching device, or within the transformer itself.

The secondary winding of the step-down transformer constitutes the point of origin of a new electrical system. Ground-fault currents associated with the radiating secondary circuits return to this point. Hence, all secondary circuit protective conductors are brought to a common junction point at this source transformer. For grounded system operation, this common junction point is bonded to the grounded circuit conductor (on the supply side of any overcurrent device or disconnecting means), to the source transformer frame or other metal enclosures, and to any adjacent metal member of the building structure or piping system if available. Should the secondary system be exposed to external sources of overvoltage surges, such as lightning, a check should be made to ensure the existence of an adequate grounding electrode connected to the central junction of secondary protective conductors.

In general, the grounding electrode will be present for system grounding; however, the requirements for system grounding may not be adequate for the dissipation of lightning surges.

In most cases, one should observe that the primary and secondary protective conductor systems become interconnected at the step-down substation. This happens because the metal enclosure at the substation encloses energized conductors of both the primary system and the secondary system. Functionally, the two protective conductor systems are independent of each other. (Had the transformation station consisted of an independent generator belt driven from an electric drive motor, the independence of the two protective conductor systems would have been self-evident.)

10. Utilization equipment

The equipment grounding and bonding function at utilization equipment consists simply of providing an effective bonding connection between the non-current carrying metal parts of the terminal apparatus, which either enclose or are adjacent to energized conductors, and the protective conductor. The sizing and terminating of all such protective conductors should observe the same rules that have already been established, which depend on the rating and character of the next upstream overcurrent protective device. In many cases where the electrical metal raceway or cable armor serves as the protective conductor of the circuit, the bonding connection to the utilization equipment frame consists simply of a good mechanical connection where the metal raceway terminates at the connection box or metal side or roof sheet of the terminal apparatus.

A bonding connection to an adjacent building metal structure in the case of fixed equipment is appropriate although somewhat redundant. A separate protective conductor wire provides added assurance of continuity of the equipment ground.

Figure 11 displays the desired equipment to protective conductor connection arrangement for a variety of power circuit patterns and clearly displays the distinction between the protective and the neutral conductors for fixed equipment. Figure 12 displays a similar arrangement for portable equipment.

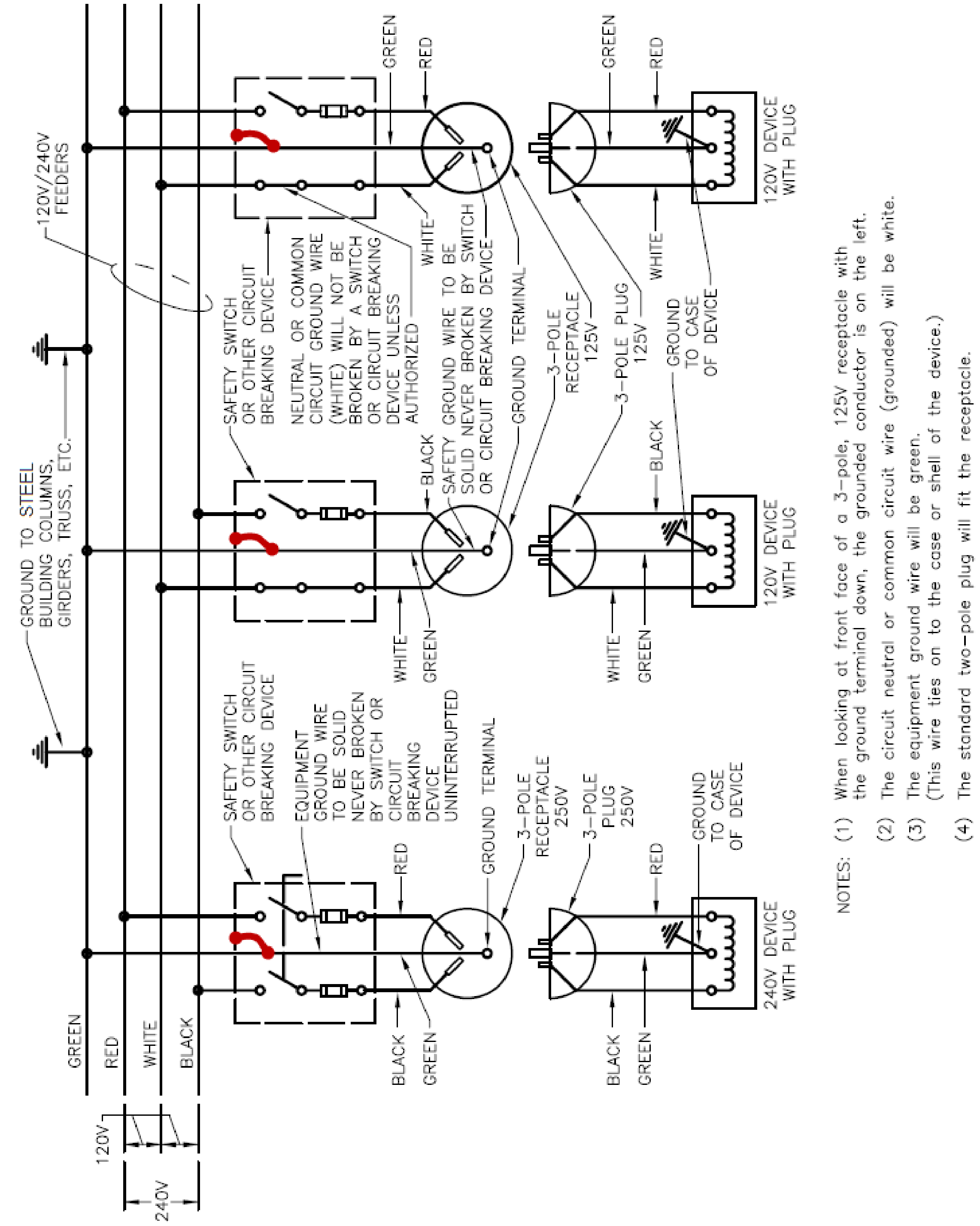


Figure 11 —Typical supply conductor patterns of power circuits of utilization apparatus with emphasis on a distinction between protective and grounded conductors of fixed equipment

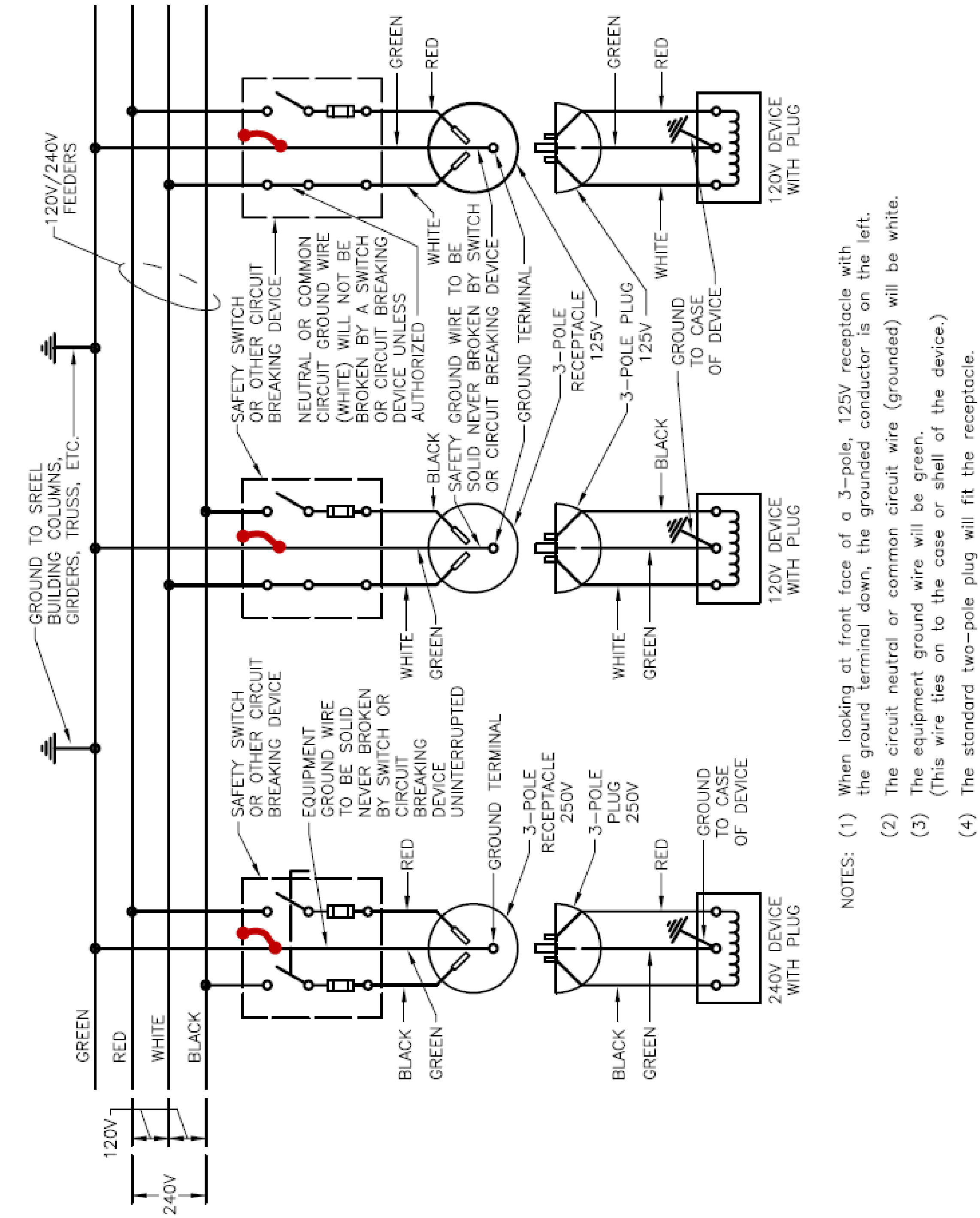


Figure 12—Typical supply conductor patterns of power circuits of utilization apparatus with emphasis on a distinction between protective and neutral conductors of portable equipment

Annex A

(informative)

Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

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